BDNF Val66Met moderates memory impairment, hippocampal function and tau in preclinical autosomal dominant Alzheimer’s disease

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Abstract

Background: The brain-derived neurotrophic factor (BDNF) Val66Met polymorphism is implicated in synaptic excitation and neuronal integrity, and has previously been shown to moderate Aβ-related memory decline and hippocampal atrophy in preclinical sporadic Alzheimer’s disease (AD). However, the effect of BDNF in autosomal dominant AD (ADAD) is unknown. We aimed to determine the effect of BDNF Val66Met on cognitive function, hippocampal function, tau and Aβ in preclinical ADAD. We explored effects of apolipoprotein E (APOE) ε4 on these relationships.

Methods: The Dominantly Inherited Alzheimer Network (DIAN) conducted clinical, neuropsychological, genetic, biomarker and neuroimaging measures at baseline in 131 mutation non-carriers (NC) and 143 preclinical ADAD mutation carriers (MC) on average 12 years prior to clinical symptom onset. BDNF genotype data were obtained for MCs (95 Val66 homozygotes, 48 Met66 carriers).

Findings: Among preclinical MCs, Met66 carriers had worse memory performance, lower hippocampal glucose metabolism and increased levels of CSF tau and phosphorylated tau (p-tau) than Val66 homozygotes. Cortical Aβ and CSF Aβ42 levels were significantly different from NC’s but did not differ between preclinical MC Val66 homozygotes and Met66 carriers. There was an effect of APOE on Aβ levels but not cognitive function, glucose metabolism or tau.

Interpretation: As in sporadic AD, the deleterious effects of Aβ on memory, hippocampal function, and tau in preclinical ADAD mutation carriers are greater in Met66 carriers. To date, this is the only genetic factor found to moderate downstream effects of Aβ in ADAD.
Introduction

Alzheimer’s disease (AD) begins with the aggregation of beta-amyloid (Aβ), the development and spread of hyperphosphorylated tau (Ballatore *et al*., 2007, Ittner and Götz, 2011), and ultimately neuronal and synaptic loss. This characteristic pathological process manifests initially as cognitive impairment which increases progressively so eventually classification of dementia is warranted (Hardy and Higgins, 1992, Ittner and Götz, 2011, Spires-Jones and Hyman, 2014). Clinical pathological relationships in AD are still not understood completely, however recent *in vitro* (Hariri *et al*., 2003, Lee *et al*., 2012), *post-mortem* (Buchman *et al*., 2016, Garzon and Fahnestock, 2007, Peng *et al*., 2005) and animal (Caccamo *et al*., 2010, Lee *et al*., 2012, Rosa and Fahnestock, 2015) studies suggest neurotrophic factors, such as brain-derived neurotrophic factor (BDNF) moderate neuronal and synaptic dysfunction and their behavioral expression in AD (Fahnestock, 2011, Lu *et al*., 2013).

Clinical studies of the role of BDNF in AD are limited by the absence of validated biomarkers for central nervous system (CNS) BDNF (Forlenza *et al*., 2010, Kim *et al*., 2015). However, the BDNF Val66Met (rs6265) polymorphism Met protein can result in reduced dendritic trafficking and synaptic localization of the protein and up to a 30% reduction in activity-dependent BDNF secretion (Chen *et al*., 2006, Egan *et al*., 2003). In healthy young adults, memory dependent hippocampal activity is reduced in Met66 carriers (Hariri *et al*., 2003). In the preclinical and prodromal stages of sporadic AD, prospective studies show Met66 carriers to have increased rates of decline in episodic memory and hippocampal atrophy relative to Val66 homozygotes (Feng *et al*., 2013, Lim *et al*., 2014, Lim *et al*., 2013, Lim *et al*., 2014). These same studies observe rates of cortical Aβ accumulation to be unaffected by the Met66 allele (Lim *et al*., 2014, Lim *et al*., 2013), suggesting that BDNF Met66 may accelerate neuronal dysfunction and memory decline by moderating pathological processes downstream of cortical Aβ accumulation, such as tau aggregation.

While the processes that give rise to cortical Aβ accumulation are likely to differ between sporadic and autosomal dominant AD, the effects of Aβ on neurodegeneration and cognition are similar, albeit occurring at markedly younger ages in ADAD (mean age of onset is 45 years) (Bateman *et al*., 2012, Jack and Holtzman, 2013, Ryman *et al*., 2014). Therefore the aim of this study was to investigate the effects of the BDNF Met66
allele on episodic memory, hippocampal function, Aβ and tau in ADAD. The first hypothesis was that in preclinical ADAD mutation carriers (MCs), impairment in episodic memory and hippocampal function would be greater in individuals who carry at least one copy of the BDNF Met66 allele compared to Val66 homozygotes. The second hypothesis was that cortical Aβ levels would be unrelated to variation in BDNF Val66Met. The third hypothesis was that CSF tau levels would be greater in BDNF Met66 carriers compared to Val66 homozygotes. We also explored the extent to which carriage of the BDNF Met66 allele was associated with domains of cognition beyond episodic memory, neuronal function in the precuneus and CSF biomarkers of Aβ_{1-42} and phosphorylated tau (p-tau_{181}). Finally, while the apolipoprotein E (APOE) ε4 allele does not increase severity of clinical presentation in ADAD (Ryman et al., 2014), we observed previously additive effects of the BDNF Met66 and APOE ε4 alleles on Aβ related cognitive decline in preclinical sporadic AD (Lim et al., 2014). Therefore, we also explored the extent to which APOE acts independently, or with BDNF, to impact disease processes in ADAD.

**Method**

**Participants**

Individuals at risk for carrying a mutation for ADAD (i.e., presenilin 1 [PSEN1], presenilin 2 [PSEN2], or amyloid precursor protein [APP] mutations) were enrolled in the Dominantly Inherited Alzheimer Network (DIAN) study. Participants from families with known pathogenic ADAD mutations were recruited from 197 families at six sites in the United States, one in the United Kingdom and three in Australia (Morris et al., 2012). The process of recruitment and enrollment has been described in detail previously (Bateman et al., 2012, Morris et al., 2012). Baseline data from 274 participants (131 NCs, 143 preclinical MCs) who were cognitively normal, as defined by a Clinical Dementia Rating of 0, and who had completed assessments of cognitive function, neuroimaging and cerebrospinal fluid (CSF) sampling were included. APOE genotype was determined for all individuals as part of the DIAN study protocol. Additionally, for MCs, only individuals whose BDNF Val66Met polymorphism was available were included. Table 1 shows the demographic characteristics of each participant group.

**Clinical Assessment**
Without reference to participants’ performance on the neuropsychological test battery, a clinician assessed each participant for the presence and severity of clinical symptoms of dementia at baseline. This was operationalized using the Clinical Dementia Rating (CDR) scale, for which a CDR total score of 0 indicates cognitive normality (Morris, 1983). Participants also completed the Mini Mental State Examination (MMSE) and the Geriatric Depression Scale (GDS) at baseline.

Neuropsychological Assessment

All participants were assessed using the DIAN neuropsychological test battery, which includes the Wechsler Memory Scale–Revised Logical Memory (Story A only, immediate and delayed recall) and Digit Span; Category Fluency (animals, vegetables); Trail Making Test A and B; Digit Symbol from the Wechsler Adult Intelligence Scale–Revised (WAIS–R); the Boston Naming Test (30 odd items), letter fluency for F, A, and S, and immediate and delayed recall of a single presentation of a 16-item word list (Storandt et al., 2014). These tasks have been described previously, and were administered according to standard protocols by trained research assistants (Storandt et al., 2014). The process of standardization and quality control of neuropsychological assessments across all DIAN sites have also been described previously (Storandt et al., 2014).

Outcome measures for each neuropsychological test were standardized against the baseline mean and standard deviation for the NC group. Standardized scores were then averaged to form four cognitive domain-specific composite scores for episodic memory (Logical Memory delayed recall, word list learning delayed recall); executive function (Letter Fluency, Trail Making Test B); language (Category Fluency animals + vegetables, Boston Naming Test); attention (Digit Span Forwards, Digit Symbol); and global cognition (Logical Memory delayed recall, word list learning delayed recall, Digit Symbol, MMSE) (Donohue et al., 2014).

Genotyping
Genotyping for pathogenic mutations in the *APP, PSEN1*, and *PSEN2* genes were performed on DNA extracted from peripheral blood samples using methods described previously (Talbot *et al.*, 1994). Samples were also genotyped with the Infinium HumanExomeCore V1.0 Beadchip (Illumina, Inc). Genotyping was performed at The Genome Technology Access Center (GTAC; https://gtac.wustl.edu/) at Washington University. All samples and genotypes underwent stringent quality control (QC). Genotype data were cleaned by applying a minimum call rate for SNPs and individuals (98%). SNPs not in Hardy-Weinberg equilibrium (P< 1×10^{-6}) were excluded. No SNPs were removed because low mAF. Gender identification was verified by analysis of X-chromosome SNPs. We tested for unanticipated duplicates using pairwise genome-wide estimates of proportion identity-by-descent using PLINK v1.9. Genotype data for the *BDNF* Val66Met (rs6265) polymorphism was extracted from using PLINK. Clinicians were blinded to all genetic information and genetic polymorphisms were not used diagnostically. *BDNF* Val66Met genotyping was performed only in samples from individuals with a known ADAD mutation.

**Neuroimaging**

Images obtained through positron emission tomography (PET) with the use of fluorodeoxyglucose (FDG) and Pittsburgh compound B (PiB) (FDG-PET and PiB-PET, respectively) were co-registered with individual MRI images for region-of-interest (ROI) determination. 3 Tesla volumetric T1-weighted MRI scans from DIAN participants were acquired and processed through FreeSurfer (Martinos Center, Boston, MA) as previously described (Benzinger *et al.*, 2013). Amyloid imaging was performed with a bolus injection of approximately 15 mCi of [11C] PiB. Dynamic imaging acquisition started either at injection for 70 minutes or 40 minutes post-injection for 30 minutes. For analysis, PiB-PET data between 40 to 70 minutes were used. For PiB-PET, total neocortical SUVR was used to determine levels of cortical Aβ deposition, using cerebellar grey matter as the reference region and applying partial volume correction using a regional point spread function as previously described (Su *et al.*, 2015).

Metabolic imaging with [18F] FDG-PET was performed with a 3D dynamic acquisition began 40 minutes after a bolus injection of approximately 5 mCi of FDG and lasted for 20 minutes. In accordance with previous reports (Bateman *et al.*, 2012), the
ROIs selected for this study were the hippocampus and the precuneus, with decreased FDG SUVR indicating decreased glucose metabolism and therefore reduced neuronal function in that area. The reference region used was the cerebellar cortex.

Biochemical Analysis

Fasted CSF was collected in the morning via lumbar puncture. Samples were shipped on dry ice to the DIAN biomarker core laboratory. CSF concentrations of Aβ42, total tau, and tau phosphorylated at threonine 181 (p tau181) were measured by immunoassay (INNOTEST β-Amyloid1-42, Innogenetics). All values had to meet quality-control standards, including a coefficient of variation of 25% or less, kit “controls” within the expected range as defined by the manufacturer, and measurement consistency between plates of a common sample that was included in each run.

Estimated year of onset

The estimated year from expected symptom onset (EYO) was calculated as the age of the participant at the time of the baseline assessment minus the mean age at onset of all other individuals with the same mutation type (Ryman et al., 2014).

Data Analysis

The study hypotheses that in ADAD, MC BDNF Met66 carriage would be associated with greater impairment in memory, greater and higher CSF tau but not cortical AB levels were tested by submitting the episodic memory composite, PiB-PET Aβ, CSF tau and glucose metabolism in the hippocampus (FDG-PET) to separate analyses of covariance (ANCOVA). In each ANCOVA, EYO was added as a covariate, and Group (NC, MC Val66/Val66, MC Met66) as a fixed factor. Within each ANCOVA, two planned comparisons were constructed with the first comparing MC Val66 homozygotes and MC Met66 carriers and the second comparing MC Val66 homozygotes to the NC group. Exploratory analyses were conducted only if a statistically significant difference between the MC Val66 homozygote and MC Met66 carrier groups was observed for at least one of the primary outcome measures. With this criterion met, the ANCOVAs were repeated for the remaining cognitive composite scores, CSF Aβ42, CSF p-tau181, and FDG-PET in the precuneus. The extent to which the
presence of the APOE ε4 allele influenced the effect of BDNF on cognitive function, Aβ burden, tau and neuronal function was determined by repeating these analyses with ε4 status (carrier vs. non-carriers) entered into all statistical models. Finally, to further understand the effect of BDNF Val66Met on cognitive and biomarker outcomes in ADAD, we expressed each cognitive and biomarker outcome variable as a function of EYO. For the primary outcomes, statistical significance was classified as $p<.05$. This was to balance the risk of false positive findings against the identification of important relationships because (a) this is an exploratory investigation in a relatively new area in which an important clinical issue has been identified, (b) as all four primary outcome measures are recognized as part of the AD pathological process, changes in these will be correlated and (c) effect sizes (Cohen’s d) were used to guide interpretation about the meaningfulness of statistical tests and comparisons with effect sizes $<0.2$ were classified as trivial and not interpreted regardless of statistical significance (Cohen, 1988).

**Results**

**Demographic and clinical characteristics**

MCs were significantly younger than NCs, although the EYO between MC Val66 homozygotes and MC Met66 carriers did not differ significantly. NC and MC groups did not differ on any other demographic characteristic. While the inclusion criteria required all individuals to have a CDR score of 0, the CDR sum of boxes score was significantly higher in MC Met66 carriers than in MC Val66 homozygotes and NCs (Table 1). Groups did not differ in MMSE total scores or levels of depressive symptoms.

**Effect of BDNF Val66Met on episodic memory, cortical Aβ, CSF tau and glucose metabolism in the hippocampus**

Group means and standard deviations for raw scores on each of the primary outcome cognitive and biomarker measures for each group are summarized on Table 2. The outcomes of the primary analyses are summarized on Figure 1 for episodic memory and Figure 2 for the AD biomarkers. Statistically significant group differences between MC Val66 homozygotes and MC Met66 carriers were observed for episodic memory (Figure 1), glucose metabolism in the hippocampus and CSF tau, but not cortical Aβ (Figure 2). Effect sizes for these comparisons were, by convention, moderate-to-large in
magnitude for episodic memory, glucose metabolism in the hippocampus and CSF tau levels, but were trivial for levels of cortical Aβ. No statistically significant differences between NC and MC Val66 homozygotes were observed for any of the primary outcome measures, with all differences small in magnitude.

**Effect of BDNF Val66Met on cognition, CSF Aβ42, CSF p-tau181 and glucose metabolism in the precuneus**

For each exploratory cognitive and biomarker outcome measure, group raw group means and standard deviations for raw scores on each of the primary outcome cognitive and biomarker measures for each group are also summarized on Table 2. Figure 1 and 2 also summarizes the outcomes of the exploratory analyses are summarized on Figure 1 for cognitive measures and Figure 2 for the AD biomarkers respectively. Statistically significant group differences, of a moderate-to-large magnitude, were observed between MC Val66 homozygotes and MC Met66 carriers for CSF p-tau181 levels (Figure 2, exploratory outcomes) but not for glucose metabolism in the precuneus or for the executive function, language, attention or global cognition composites (Figure 1, exploratory outcomes). There were also no statistically significant differences between MC Val66 homozygotes and MC Met66 carriers on CSF Aβ42 levels, with these differences small in magnitude (Figure 2, exploratory outcomes).

When compared to NCs, MC Val66 homozygotes showed no statistically significant impairment in any domain of cognitive function (Figure 1) and did not differ significantly in the extent of glucose metabolism in the hippocampus or the precuneus (Figure 2). Compared to NCs, both MC Val66 homozygotes and MC Met66 carriers showed elevated levels of CSF tau and p-tau181, and increased PiB-PET SUVR and decreased CSF Aβ42 levels (Table 2).

**Effect of APOE ε4 on cognitive function, neuronal dysfunction, Aβ and tau**

Re-analyses of the primary hypotheses with the addition of APOE status indicated no significant main effect of APOE status and no significant interaction between APOE and BDNF status on any measure of cognitive function (Table 3). Similarly, there was no significant main effect of APOE or interaction between APOE and BDNF for any outcome measure of glucose metabolism or tau (Table 3). However, there
was a significant main effect of *APOE* for both PiB-PET SUVR and CSF Aβ₄₂, although there were no significant interactions between *APOE* and *BDNF* for either measure (Table 3). Post-hoc analyses showed that when compared to MC ε4 non-carriers, MC ε4 carriers had significantly increased PiB-PET SUVR (d [95%CI = 0.45 [0.05, 0.85], *p* = .03) and decreased CSF Aβ₄₂ levels (d [95%CI = 0.76 [0.34, 1.17], *p* < .001).

**Effect of BDNF Val66Met on the relationship between EYO and markers of cognitive and neuronal function, Aβ and tau**

There were no statistically significant relationships between level of cognitive function and EYO in NCs or in MC Val₆₆ homozygotes. However, the relationship between EYO and episodic memory was statistically significant and moderate in magnitude for MC Met₆₆ carriers (Figure 3A). Similarly, there were no statistically significant relationships between glucose metabolism in the hippocampus and EYO in NCs or in MC Val₆₆ homozygotes. However, the relationship between glucose metabolism in the hippocampus and EYO was moderate in magnitude and statistically significant for MC Met₆₆ carriers (Figure 3B).

There was no relationship between levels of cortical Aβ and EYO in NCs, but there was a significant moderate association between cortical Aβ levels and EYO in MCs irrespective of *BDNF* Val66Met polymorphism (Figure 3C). Similarly, while there was no association between CSF tau and EYO in NCs, there was a significant moderate association between CSF tau and EYO in MCs, irrespective of *BDNF* Val66Met genotype (Figure 3D), with MC Met₆₆ carriers showing systematically higher levels of CSF tau relative to their EYO than MC Val₆₆ homozygotes (Figure 3D).

**Discussion**

The results show that the presence of one copy of the *BDNF* Met₆₆ allele increased the severity of impairment in episodic memory and hippocampal function in preclinical ADAD. This effect is clinically important as the magnitude of memory impairment related to MC Met₆₆ carriers was approximately double that observed in MC Val₆₆ homozygotes. These findings in the DIAN cohort are consistent with the greater memory decline and hippocampal volume loss observed in older adults with preclinical or prodromal sporadic AD from the AIBL and ADNI studies (Feng *et al.*, 2013, Lim *et al.*, 2013).
The results confirm therefore, in an independent sample, that *BDNF* is important to the preclinical presentation of AD.

The current data support the first hypothesis that in preclinical MCs, impairment in memory and hippocampal function would be greater in Met<sub>66</sub> carriers compared to Val<sub>66</sub> homozygotes. Compared to MC Val<sub>66</sub> homozygotes, MC Met<sub>66</sub> carriers had worse episodic memory function (Figure 1). In contrast, no memory impairment was observed in MC Val<sub>66</sub> homozygotes compared to NCs. Similarly, hippocampal function, determined by cerebral glucose metabolism, was also reduced in MC Met<sub>66</sub> carriers compared to MC Val<sub>66</sub> homozygotes. However, MC Val<sub>66</sub> homozygotes did not show lower glucose metabolism compared to NCs. As increased oxidative stress has been previously observed in females (Keaney et al., 2003), it is possible that the sex of participants may better account for the memory impairment in MC Met<sub>66</sub> carriers. However, re-analysis of all primary outcome measures suggest that even when the sex of participants was considered, the effect of *BDNF Val66Met* on memory impairment, hippocampal function and tau remains (Table 4). Finally, MC Met<sub>66</sub> carriers who were estimated to be nearer to their expected year of clinical symptom onset (EYO) showed increased memory impairment and lower glucose metabolism in the hippocampus (Figure 3). In contrast, EYO was not associated with memory impairment or glucose metabolism in NCs or MC Val<sub>66</sub> homozygotes.

The second hypothesis that cortical Aβ and CSF Aβ<sub>42</sub> levels would be unrelated to allelic variation in *BDNF Val66Met* was also supported. Preclinical MC Met<sub>66</sub> carriers and Val<sub>66</sub> homozygotes had equivalent levels of higher cortical Aβ and CSF Aβ<sub>42</sub>. Furthermore, these group differences were, by convention, small (i.e., d<0.2; Figure 2) in magnitude indicating that absence of statistically significant differences was not due to insufficient statistical power. Compared to NCs, both Met<sub>66</sub> carriers and Val<sub>66</sub> homozygotes showed increased levels of cortical Aβ deposition and decreased levels of CSF Aβ<sub>42</sub>. Similarly, cortical Aβ burden was higher in preclinical MCs who were nearer to their EYO; although this relationship was not moderated by the *BDNF Val66Met* polymorphism (Figure 3C). Increased cortical Aβ and lower CSF Aβ<sub>42</sub> levels have been observed previously in preclinical ADAD (Bateman et al., 2012, Ryman et al., 2014). The absence of any effect of Met<sub>66</sub> carriage on Aβ burden in preclinical ADAD is also consistent with observations that Met carriage was unrelated to rates of cortical Aβ
accumulation over 3 years in preclinical and prodromal sporadic AD (Feng et al., 2013, Lim et al., 2014, Lim et al., 2013). Together, these findings suggest that the effect of the \textit{BDNF} Met\textsubscript{66} allele is independent of the effect of A\textsubscript{β} on risk for, and progression of, AD.

The results also support the third hypothesis that CSF levels of tau would be greater in MC Met\textsubscript{66} carriers compared to MC Val\textsubscript{66} homozygotes. Levels of both CSF tau and p-tau\textsubscript{181} were increased substantially in preclinical MC Met\textsubscript{66} carriers compared to preclinical MC Val\textsubscript{66} homozygotes (Figure 2). Compared to NCs, preclinical MC Val\textsubscript{66} homozygotes also showed increased levels of CSF tau and p-tau\textsubscript{181}, although not to the same extent as MC Met\textsubscript{66} carriers. Despite the overall increase in these biochemical markers, strong relationships between EYO and CSF tau were observed in both MC Val\textsubscript{66} homozygotes and MC Met\textsubscript{66} carriers, and the magnitude of these relationships were equivalent (Figure 3D). Thus, while the Met\textsubscript{66} allele hastens memory dysfunction in preclinical ADAD, it does not necessarily affect the rate at which p-tau\textsubscript{181} accumulates in CSF. Instead, substantial differences in CSF p-tau\textsubscript{181} levels between MC Met\textsubscript{66} carriers and MC Val\textsubscript{66} homozygotes (Figure 2) suggest that MC Val\textsubscript{66} homozygotes may have an increased level of resilience to the neurotoxic effects of tau and A\textsubscript{β}.

Finally, we explored the extent to which \textit{APOE} acts independently or with \textit{BDNF} to impact disease processes in ADAD. There were no independent effects of \textit{APOE} ε4, or combined effects of \textit{APOE} and \textit{BDNF}, on cognition, neuronal function or CSF tau (Table 3). However, compared to MC ε4 non-carriers, MC ε4 carriers showed increased cortical A\textsubscript{β} and decreased CSF A\textsubscript{β}42. This indicates that in preclinical ADAD, the abnormal accumulation of cortical A\textsubscript{β} resulting from pathogenic mutations is increased further by the \textit{APOE} ε4 allele, although this increased A\textsubscript{β} was not associated with any greater impairment in cognition or neuronal function. Importantly, the increase in cortical A\textsubscript{β} in MC ε4 carriers was not affected by the \textit{BDNF} Met allele. Thus, allelic variation in \textit{BDNF} and \textit{APOE} may affect different AD processes with ε4 increasing cortical A\textsubscript{β} accumulation and \textit{BDNF} Met\textsubscript{66} moderating A\textsubscript{β} related impairment in cognition and neuronal function through its effects on tau.

Neuronal and synaptic loss characteristic of both sporadic and autosomal dominant AD is due to the combined accumulation of A\textsubscript{β} plaques and tau aggregation (Ballatore et al., 2007, Ittner and Götz, 2011, Spires-Jones and Hyman, 2014).
Neuropathological and CSF biomarker studies show that in AD, cognitive impairment and synaptic loss are associated more strongly with the presence and number of neurofibrillary tangles than Aβ plaques (Bennett et al., 2004, Giannakopoulos et al., 2003, Ingelsson et al., 2004). However, neuroimaging studies in preclinical AD report that higher cortical Aβ load is associated with greater rates of cognitive decline and progression to MCI (Lim et al., 2014, Rowe et al., 2013), with these effects mediated by the effect of Aβ on neurodegeneration (Jack and Holtzman, 2013, Lim et al., 2015). In this context, dissociation of the effects of BDNF on Aβ and tau associated cognitive impairment observed here are important because they provide evidence that BDNF Met66 influences disease progression through effects on neuronal dysfunction and cognitive impairment associated with tau.

The current observation that BDNF Met66 in preclinical ADAD was associated with increased tau, hippocampal dysfunction and memory impairment is consistent with the role that CNS BDNF plays in synaptic excitation, long-term potentiation and neuronal plasticity (Fahnestock, 2011, Forlenza et al., 2010, Garzon and Fahnestock, 2007, Hariri et al., 2003, Lee et al., 2012, Lu et al., 2013, Peng et al., 2005). Evidence of a mechanistic relationship between BDNF and tau has been shown in cellular studies which demonstrate that BDNF can induce rapid dephosphorylation of tau through TrkB activation (Elliott et al., 2005) and that BDNF loss in AD is specific to tangle-bearing neurons (Ferrer et al., 1999). This has prompted the hypothesis that there may be a direct relationship between CNS BDNF levels and tau (Belrose et al., 2013), although this remains under investigation. Even in the absence of a direct mechanistic link, the large and clinically important effects of BDNF Met66 on memory, hippocampal function and tau, observed in the current ADAD sample, indicate that studying allelic variation in BDNF Val66Met may help clarify pathological models of AD and may even provide a reference for the investigation of the effects and clinical consequences of other neurotrophic factors in AD.

As we have noted (Lim et al., 2013), genome-wide association studies (GWAS) of AD do not identify the BDNF Val66Met polymorphism as increasing the risk for AD (Lambert et al., 2013). One possible explanation for this is that GWAS typically use a clinical classification of dementia as the target phenotype. Consequently, they may overlook the contribution of BDNF because the effects of this gene manifest only in the
earliest stages of the disease (Feng et al., 2013, Lim et al., 2014, Lim et al., 2013). This hypothesis is supported by GWAS of cognitive aging in non-demented older adults, where BDNF Val66Met has been associated with memory impairment and decline (Harris and Deary, 2011, Papenberg et al., 2015). Thus, the hypothesis arising from the current and previous studies (Lim et al., 2014, Lim et al., 2013, Lim et al., 2014) is that in studies of cognitive aging, memory decline associated with BDNF Met66 may reflect occult AD as opposed to the effects of normal aging. In contrast to BDNF, GWAS of AD identify carriage of APOE ε4 as increasing risk for AD (Lambert et al., 2013). We have also reported that in preclinical sporadic AD, the APOE ε4 allele increases the rate of memory decline and brain volume loss associated with high Aβ (Dore et al., 2013, Lim et al., 2014, Lim et al., 2015). We have also observed that Aβ+ older adults who carry both the APOE ε4 and BDNF Met66 allele show greater memory decline than those who carry either one by itself (Lim et al., 2014). Re-analysis of the current data taking into account APOE ε4 did not indicate any effect of APOE or any interaction between APOE and BDNF on cognition (Table 3). The absence of any effect of APOE on cognition in this study is consistent with the results of a detailed meta-analysis of three ADAD cohorts which showed that APOE did not moderate age of clinical symptom onset (Ryman et al., 2014). However, despite having no effect on cognitive function or clinical symptom onset, APOE ε4 was associated with increasing cortical Aβ levels in preclinical MCs. Consequently, one hypothesis for the absence of any APOE effect on cognitive and clinical outcomes in ADAD is that these outcomes are related more strongly to neuronal dysfunction and tau than to Aβ accumulation.

This study demonstrates that the deleterious effects of Aβ in ADAD were increased in preclinical individuals who carried the BDNF Met66 allele. Therefore, the results of this study also confirm the similarity between the development of dementia in ADAD and sporadic AD. However, as the current findings are based on cross-sectional data, it will be necessary to replicate these results prospectively. Nonetheless, the strength and consistency of our results with that in sporadic AD is important because they suggest that strategies designed to increase CNS BDNF levels may be a viable therapeutic alternative or addition to those which seek to reduce the neurotoxic effects of Aβ. Our results also suggest strongly that the BDNF Val66Met polymorphism should be considered as a potential moderator of clinical trial outcomes in current treatment
and prevention trials in ADAD and sporadic AD (Donohue et al., 2014, Mills et al., 2013).

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Drafting the manuscript: YY Lim, J Hassenstab, P Maruff, RJ Bateman

Interpretation of data: YY Lim, J Hassenstab, P Maruff, RJ Bateman

Revising the manuscript: YY Lim, J Hassenstab, C Cruchaga, A Goate, AM Fagan, TLS Benzinger, P Maruff, PJ Snyder, CL Masters, R Allegri, J Chhatwal, MR Farlow, NR Graff-Radford, C Laske, J Levin, E McDade, JM Ringman, M Rossor, S Salloway, PR Schofield, DM Holtzman, JC Morris, RJ Bateman

Conflicts of Interests

YY Lim, J Hassenstab, C Cruchaga, P Maruff, PJ Snyder, R Allegri, MR Farlow, NR Graff-Radford, C Laske, E McDade, and J Ringman have no disclosures.

A Goate reports grants from NIH, during the conduct of the study and personal fees from Denali Therapeutics, outside the submitted work. AM Fagan reports grants from NIH/NIA, during the conduct of the study, and personal fees from Roche, IBL International, and DiamiR, outside the submitted work. TLS Benzinger reports grants from NIH, during the conduct of the study, and grants from NIH, Avid Radiopharmaceuticals (Eli Lilly), Eli Lilly, and Roche outside the submitted work. CL Masters is a consultant to Prana Biotechnology, Eli Lilly and Actinogen. J Chhatwal reports grants from BrightFocus Foundation, National Institute on Aging, and American Brain Foundation outside the submitted work. J Levin reports grants from DZNE (German Center for Neurodegenerative Diseases), during the conduct of the study; personal fees from Bayer Vital, General Electric, and Willi Gross Foundation; grants from Verum Foundation, ParkinsonFonds Deutschland gGmbH, Deutsche Parkinson Vereinigung, Deutsche Stiftung Neurologie, and Golser Foundation outside the submitted work. M Rossor reports grants from the National Institute on Aging during the conduct of the study. S Salloway reports grants and personal fees from Biogen, Merck, Eli Lilly, Roche and Genentech; and grants from Avid and Functional Neuromodulation outside the submitted work. PR Schofield reports grants from
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Table 1. Demographic and clinical characteristics

<table>
<thead>
<tr>
<th></th>
<th>NC (n=131)</th>
<th>MC Val&lt;sub&gt;66&lt;/sub&gt;/Val&lt;sub&gt;66&lt;/sub&gt; (n=95)</th>
<th>MC Met&lt;sub&gt;66&lt;/sub&gt; (n=48)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (%) Female</td>
<td>58 (44.3%)</td>
<td>37 (38.9%)</td>
<td>25 (52.1%)</td>
<td>.325</td>
</tr>
<tr>
<td>N (%) APOE ε4 carrier</td>
<td>39 (29.8%)</td>
<td>24 (25.3%)</td>
<td>12 (25.0%)</td>
<td>.784</td>
</tr>
<tr>
<td>Age</td>
<td>38.37 (10.13)</td>
<td>34.45 (8.54)</td>
<td>35.12 (9.51)</td>
<td>.012</td>
</tr>
<tr>
<td>Est. Year of Onset</td>
<td>N/A</td>
<td>-12.44 (8.11)</td>
<td>-12.70 (7.60)</td>
<td>.855</td>
</tr>
<tr>
<td>Years of Education</td>
<td>14.79 (2.64)</td>
<td>14.72 (3.54)</td>
<td>14.24 (2.56)</td>
<td>.328</td>
</tr>
<tr>
<td>GDS</td>
<td>1.24 (1.66)</td>
<td>1.45 (1.83)</td>
<td>1.47 (1.60)</td>
<td>.566</td>
</tr>
<tr>
<td>CDR sum of boxes</td>
<td>0.01 (0.06)</td>
<td>0.02 (0.10)</td>
<td>0.06 (0.17)</td>
<td>.005</td>
</tr>
<tr>
<td>MMSE</td>
<td>29.20 (1.17)</td>
<td>28.97 (1.37)</td>
<td>29.04 (0.99)</td>
<td>.340</td>
</tr>
</tbody>
</table>

Note: NC = Mutation non-carrier; MC = mutation carrier; GDS = Geriatric Depression Scale; HADS = Hospital Anxiety and Depression Scale; MACQ = Memory Complaints Questionnaire; CDR = Clinical Dementia Rating scale; MMSE = Mini-Mental State Examination
Table 2. Differences in each cognitive marker and biomarker between mutation non-carriers, mutation carriers who are *BDNF Val*<sup>66</sup> homozygotes, and mutation carriers who are *BDNF Met*<sup>66</sup> carriers.

<table>
<thead>
<tr>
<th>Primary Outcomes</th>
<th>EYO (df) F</th>
<th>Group (df) F</th>
<th>NC Mean (SD)</th>
<th>N</th>
<th>MC Val&lt;sup&gt;66&lt;/sup&gt;/Val&lt;sup&gt;66&lt;/sup&gt; Mean (SD)</th>
<th>N</th>
<th>MC Met&lt;sup&gt;66&lt;/sup&gt; Mean (SD)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Episodic Memory</td>
<td>(1,268) 20.87 .00</td>
<td>(2,268) 5.35 .00</td>
<td>0.03 (0.82)</td>
<td>131</td>
<td>-0.12 (0.83)</td>
<td>95</td>
<td>-0.43 (0.83)</td>
<td>48</td>
</tr>
<tr>
<td>PIB-PET SUVR</td>
<td>(1,223) 18.31 .00</td>
<td>(2,223) 38.85 .00</td>
<td>1.04 (0.54)</td>
<td>106</td>
<td>1.62 (0.53)</td>
<td>82</td>
<td>1.74 (0.53)</td>
<td>39</td>
</tr>
<tr>
<td>CSF tau</td>
<td>(1,216) 16.20 .00</td>
<td>(2,216) 19.94 .00</td>
<td>57.18 (40.42)</td>
<td>101</td>
<td>82.83 (40.29)</td>
<td>80</td>
<td>102.15 (40.29)</td>
<td>39</td>
</tr>
<tr>
<td>FDG-PET hippocampus</td>
<td>(1,225) 12.13 .00</td>
<td>(2,225) 3.91 .02</td>
<td>1.25 (0.09)</td>
<td>109</td>
<td>1.26 (0.09)</td>
<td>80</td>
<td>1.21 (0.09)</td>
<td>40</td>
</tr>
<tr>
<td>Executive Function</td>
<td>(1,268) 2.23 .14</td>
<td>(2,268) 2.10 .12</td>
<td>0.02 (0.80)</td>
<td>131</td>
<td>-0.15 (0.81)</td>
<td>95</td>
<td>-0.22 (0.81)</td>
<td>48</td>
</tr>
<tr>
<td>Language</td>
<td>(1,267) 0.28 .60</td>
<td>(2,267) 2.90 .06</td>
<td>0.03 (0.86)</td>
<td>131</td>
<td>-0.15 (0.86)</td>
<td>95</td>
<td>-0.29 (0.86)</td>
<td>48</td>
</tr>
<tr>
<td>Attention</td>
<td>(1,268) 2.20 .14</td>
<td>(2,268) 4.00 .02</td>
<td>0.01 (0.81)</td>
<td>131</td>
<td>-0.15 (0.81)</td>
<td>95</td>
<td>-0.37 (0.81)</td>
<td>48</td>
</tr>
<tr>
<td>Global Cognition</td>
<td>(1,267) 8.36 .00</td>
<td>(2,267) 3.58 .03</td>
<td>0.02 (0.65)</td>
<td>131</td>
<td>-0.12 (0.65)</td>
<td>95</td>
<td>-0.26 (0.66)</td>
<td>48</td>
</tr>
<tr>
<td>CSF Aβ&lt;sub&gt;42&lt;/sub&gt;</td>
<td>(1,213) 8.03 .01</td>
<td>(2,213) 7.55 .00</td>
<td>430.72 (147.29)</td>
<td>99</td>
<td>355.78 (146.91)</td>
<td>78</td>
<td>346.57 (146.79)</td>
<td>40</td>
</tr>
<tr>
<td>CSF p-tau&lt;sub&gt;181&lt;/sub&gt;</td>
<td>(1,217) 8.12 .01</td>
<td>(2,217) 32.22 .00</td>
<td>29.27 (22.75)</td>
<td>101</td>
<td>48.48 (22.69)</td>
<td>80</td>
<td>60.62 (22.67)</td>
<td>40</td>
</tr>
<tr>
<td>FDG-PET precuneus</td>
<td>(1,225) 4.62 .03</td>
<td>(2,225) 1.13 .33</td>
<td>2.79 (0.29)</td>
<td>109</td>
<td>2.74 (0.29)</td>
<td>80</td>
<td>2.73 (0.29)</td>
<td>40</td>
</tr>
</tbody>
</table>

Note: EYO = estimated year of symptom onset; Group = effect of group membership as NC, MC Val<sup>66</sup> homozygote or MC Met<sup>66</sup> carrier; all models have been adjusted for estimated year of symptom onset; bolded values are significant at the p < .05 or p < .001 level.
Table 3. Effect of estimated year of symptom onset (EYO), APOE ε4 status, BDNF Val66Met status, and the interaction between APOE and BDNF on each cognitive and biomarker outcome measure

<table>
<thead>
<tr>
<th>Primary Outcomes</th>
<th>EYO (df) F</th>
<th>p</th>
<th>APOE Group (df) F</th>
<th>p</th>
<th>BDNF Group (df) F</th>
<th>p</th>
<th>APOE x BDNF Group (df) F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Episodic Memory</td>
<td>(1,266) 19.32</td>
<td>.00</td>
<td>(1,266) 1.79</td>
<td>.18</td>
<td>(1,266) 3.84</td>
<td>.05</td>
<td>(1,266) 0.08</td>
<td>.77</td>
</tr>
<tr>
<td>PiB-PET SUVR</td>
<td>(1,221) 16.73</td>
<td>.00</td>
<td>(1,221) 7.21</td>
<td>.01</td>
<td>(1,221) 2.65</td>
<td>.11</td>
<td>(1,221) 1.18</td>
<td>.28</td>
</tr>
<tr>
<td>CSF tau</td>
<td>(1,214) 15.50</td>
<td>.00</td>
<td>(1,214) 0.24</td>
<td>.63</td>
<td>(1,214) 4.06</td>
<td>.04</td>
<td>(1,214) 0.05</td>
<td>.82</td>
</tr>
<tr>
<td>FDG-PET hippocampus</td>
<td>(1,223) 11.88</td>
<td>.00</td>
<td>(1,223) 0.05</td>
<td>.83</td>
<td>(1,223) 6.03</td>
<td>.02</td>
<td>(1,223) 0.09</td>
<td>.77</td>
</tr>
</tbody>
</table>

Exploratory Outcomes

<table>
<thead>
<tr>
<th>Primary Outcomes</th>
<th>EYO (df) F</th>
<th>p</th>
<th>APOE Group (df) F</th>
<th>p</th>
<th>BDNF Group (df) F</th>
<th>p</th>
<th>APOE x BDNF Group (df) F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive Function</td>
<td>(1,266) 2.50</td>
<td>.12</td>
<td>(1,266) 0.93</td>
<td>.34</td>
<td>(1,266) 0.08</td>
<td>.78</td>
<td>(1,266) 0.08</td>
<td>.78</td>
</tr>
<tr>
<td>Language</td>
<td>(1,266) 0.20</td>
<td>.65</td>
<td>(1,266) 0.39</td>
<td>.54</td>
<td>(1,266) 0.99</td>
<td>.32</td>
<td>(1,266) 0.15</td>
<td>.70</td>
</tr>
<tr>
<td>Attention</td>
<td>(1,266) 2.40</td>
<td>.12</td>
<td>(1,266) 1.46</td>
<td>.23</td>
<td>(1,266) 2.78</td>
<td>.10</td>
<td>(1,266) 0.49</td>
<td>.49</td>
</tr>
<tr>
<td>DIAN Composite</td>
<td>(1,266) 8.14</td>
<td>.01</td>
<td>(1,266) 0.04</td>
<td>.84</td>
<td>(1,266) 0.84</td>
<td>.36</td>
<td>(1,266) 0.06</td>
<td>.81</td>
</tr>
<tr>
<td>CSF Aβ42</td>
<td>(1,211) 6.94</td>
<td>.01</td>
<td>(1,211) 9.28</td>
<td>.00</td>
<td>(1,211) 0.02</td>
<td>.90</td>
<td>(1,211) 1.39</td>
<td>.24</td>
</tr>
<tr>
<td>CSF p-tau_{181}</td>
<td>(1,215) 7.39</td>
<td>.01</td>
<td>(1,215) 2.00</td>
<td>.16</td>
<td>(1,215) 4.60</td>
<td>.03</td>
<td>(1,215) 0.34</td>
<td>.56</td>
</tr>
<tr>
<td>FDG-PET precuneus</td>
<td>(1,223) 4.82</td>
<td>.03</td>
<td>(1,223) 0.65</td>
<td>.42</td>
<td>(1,223) 0.01</td>
<td>.98</td>
<td>(1,223) 0.02</td>
<td>.91</td>
</tr>
</tbody>
</table>

Note: all models have been adjusted for estimated year of symptom onset (EYO); APOE Group indicates effect of group membership as NC, APOE ε4 carrier or APOE ε4 non-carrier; BDNF Group indicates effect of group membership as NC, MC Val_{66} homozygote or MC Met_{66} carrier; bolded values are significant at the p < .05 level
Table 4. Re-analysis of the effect of *BDNF* Val66Met on each primary outcome variable, covarying for the potential confounding effect of sex

<table>
<thead>
<tr>
<th>Outcome Variable</th>
<th>EYO (df) F</th>
<th>EYO p</th>
<th>Sex (df) F</th>
<th>Sex p</th>
<th>BDNF Group (df) F</th>
<th>BDNF Group p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Episodic Memory</td>
<td>(1,267) 13.96</td>
<td>.00</td>
<td>(1,267) 8.24</td>
<td>.00</td>
<td>(2,267) 5.17</td>
<td>.00</td>
</tr>
<tr>
<td>PiB-PET SUVR</td>
<td>(1,222) 18.43</td>
<td>.00</td>
<td>(1,222) 0.01</td>
<td>.92</td>
<td>(2,222) 40.59</td>
<td>.00</td>
</tr>
<tr>
<td>CSF tau</td>
<td>(1,215) 17.02</td>
<td>.00</td>
<td>(1,215) 0.56</td>
<td>.46</td>
<td>(2,215) 20.98</td>
<td>.00</td>
</tr>
<tr>
<td>FDG-PET hippocampus</td>
<td>(1,224) 5.60</td>
<td>.02</td>
<td>(1,224) 1.35</td>
<td>.25</td>
<td>(2,224) 3.95</td>
<td>.02</td>
</tr>
</tbody>
</table>
Figure Captions

Figure 1. Magnitude of cognitive impairment in preclinical MC Val<sub>66</sub> homozygotes and preclinical MC Met<sub>66</sub> carriers when compared to mutation non-carriers (error bars represent 95% confidence intervals) (statistical significance occurs when 95% confidence intervals do not cross “0” line).

Figure 2. Magnitude of abnormality on markers of Aβ, tau and glucose metabolism in preclinical MC Val<sub>66</sub> homozygotes and preclinical MC Met<sub>66</sub> carriers when compared to mutation non-carriers (error bars represent 95% confidence intervals) (statistical significance occurs when 95% confidence intervals do not cross “0” line).

Figure 3. Relationship between estimated year of clinical symptom onset and episodic memory performance (A), glucose metabolism in the hippocampus (B), cortical Aβ levels (C), and CSF p-tau<sub>181</sub> levels (D), in mutation non-carriers, preclinical MC Val<sub>66</sub> homozygotes, and preclinical MC Met<sub>66</sub> carriers.
Effect of BDNF Val66Met in Autosomal Dominant AD

Preclinical Mutation Carriers BDNF Val66 homozygotes
Preclinical Mutation Carriers BDNF Met66 carriers

Primary Outcome

Episodic Memory: $d (95\% CI) = 0.38 (0.02, 0.72)$
Executive Function: $d (95\% CI) = 0.09 (-0.26, 0.43)$
Language: $d (95\% CI) = 0.16 (-0.18, 0.51)$
Attention: $d (95\% CI) = 0.27 (-0.08, 0.62)$
Global: $d (95\% CI) = 0.21 (-0.14, 0.56)$

Exploratory Outcomes
### Primary Outcomes

**Exploratory Outcomes**

- **PiB-PET SUVR**
  - Preclinical Mutation Carriers BDNF Val66 homozygotes: $d$ (95%CI) = 0.23 (-0.16, 0.61)
  - Preclinical Mutation Carriers BDNF Met66 carriers: $d$ (95%CI) = 0.48 (0.09, 0.86)

- **CSF tau**
  - Preclinical Mutation Carriers BDNF Val66 homozygotes: $d$ (95%CI) = 0.56 (0.17, 0.94)
  - Preclinical Mutation Carriers BDNF Met66 carriers: $d$ (95%CI) = 0.06 (-0.32, 0.44)

- **FDG-PET Hippocampus**
  - Preclinical Mutation Carriers BDNF Val66 homozygotes: $d$ (95%CI) = 0.54 (0.15, 0.92)
  - Preclinical Mutation Carriers BDNF Met66 carriers: $d$ (95%CI) = 0.03 (-0.35, 0.41)

- **CSF Aβ42**
- **CSF ptau181**
- **FDG-PET precuneus**

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**Note:** The image contains a bar chart showing the magnitude of abnormality (compared to non-mutation carriers) for various outcomes. The chart includes data for PiB-PET SUVR, CSF tau, FDG-PET Hippocampus, CSF Aβ42, CSF ptau181, and FDG-PET precuneus, with specified effect sizes and 95% confidence intervals for both BDNF Val66 homozygotes and Met66 carriers.
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Garzon DJ, Fahnestock M. Oligomeric amyloid decreases basal levels of brain-derived neurotrophic factor (BDNF) mRNA via specific downregulation of BDNF transcripts IV and V in differentiated human neuroblastoma cells. The Journal of Neuroscience. 2007;27(10):2628-35.


